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We present the results of the structure and elemental composition of the SiO_2 layers after high-dose zinc implantation (10^{16} – 10^{17} см$^{-2}$) at room temperature and at 500°C, as well as after 700°C annealing. In the case of "hot" implantation the formation of nanosized (to 5 nm) clusters containing atoms of zinc is registered in as-implanted samples. TEM-analysis proves crystalline structure of these precipitates. Subsequent annealing results in a redistribution of zinc within the implanted layer and in the formation of large crystallites (10-12 nm for a dose of 5×10^{16} cm^{-2} and 12-18 nm for a dose of 10^{17} cm^{-2}) in the area of high impurity concentration.

FMR INVESTIGATION OF ION-BEAM SYNTHESISED IRON SILICIDES

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Ferromagnetic films Fe_3Si were synthesized by Fe^+ ion implantation in single-crystal silicon substrates during applied external magnetic field. MOKE measurements showed that all samples synthesized at specific regimes of implantation are ferromagnetic at room temperature. Magnetic field during the high-dose Fe^+ ion implantation led to the pronounced in-plane magnetic anisotropy in the synthesized films. It was shown that for isotropic samples the FMR linewidth rises with temperature decrease, whereas FMR linewidth for anisotropic samples is nearly constant with temperature variation. The experimental results are well explained in the frame of Raikher model of magnetic resonance for dynamic susceptibility of ensemble of single-domain anisotropic particles.

Introduction

The modification of magnetic properties in thin films by ion irradiation is especially useful as it can be applied to locally alter magnetic properties such as saturation magnetization, magnetic anisotropy etc. Earlier, we have used magnetic-field-assisted ion-beam synthesis to produce thin ferromagnetic silicide films Fe_3Si in single-crystal silicon substrates [1]. It was shown that application of the magnetic field during the high-dose Fe ion implantation led to the pronounced in-plane magnetic anisotropy in the synthesized films. The aim of the present work is to investigate the magnetic properties of ion-beam synthesized thin iron silicide films using the method of ferromagnetic resonance.

Experiment

40 keV Fe^+ ions were implanted into (111) single-crystal silicon wafers at room temperature. The implantation fluence was varied from 1.6×10^{17} to 3×10^{17} cm^{-2}, the ion current density being about 4 μA/cm^2. The external magnetic field H = 500 Oe was applied parallel to the sample surface during implantation.

The phase composition was investigated by X-ray diffraction using a diffractometer DRON-3M with the Cu K_α radiation at grazing incidence geometry.

The local magnetic properties of samples were investigated by scanning Kerr polarimeter in the longitudinal mode. It was found that the formation of uniaxial anisotropy is explained by the formation of small nanoparticles.

Ferromagnetic resonance spectra were recorded on a Bruker EMX spectrometer in temperature range from 100 to 300 K.

Results and Discussion

As was shown earlier the RHEED pattern obtained for Si implanted with high dose of Fe^+ ions consists of diffraction rings which are typical for polycrystalline films. The appearance of small thickenings on the diffraction rings points to a weak texture of the films. Identification of the diffraction rings showed that the reflexes correspond to polycrystalline silicides a-Fe_3Si and FeSi. Earlier [2], the results of Mossbauer spectroscopy of conversion electrons indicated the appearance of a small amount of the FeSi phase in the synthesized layer as well. X-ray diffraction at grazing angles confirms the presence of the a-Fe_3Si phase.

MOKE measurements showed that all samples synthesized at specified regimes of implantation are ferromagnetic at room temperature. The control samples implanted in the absence of the magnetic field and fixed on the sample holder without mechanical stresses are isotropic. The samples implanted with high fluences (in range from 1.6 to 2.4 cm^{-2}) of Fe ions in the applied magnetic field possess uniaxial anisotropy. The rectangular hysteresis loop and anhysteretic magnetization curve are observed in the easy and the hard magnetization axes, respectively.

The FMR signal is found to be dependent on the film orientation in the magnetic field similar to that found for the FMR in thin magnetic films. It was revealed that FMR line for anisotropic samples considerably narrower than for isotropic ones (Fig.1). Moreover, for isotropic samples the FMR linewidth rises with temperature decrease.

For isotropic samples the FMR line width rises with temperature decrease. Such dependence can be explained on the basis of model of magnetic resonance in an ensemble of single-domain anisotropic particles. The approach used based on the independent-grain model once proposed for the description of FMR in polycrystals. It should be noted that FMR linewidth for anisotropic samples is nearly constant with temperature variation. This behavior is in a good

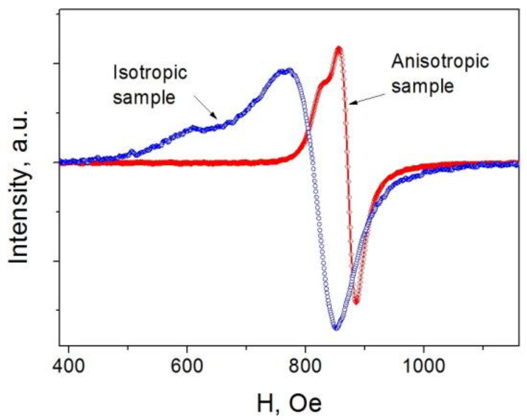

Fig. 1. In-plane geometry FMR spectra of isotropic and anisotropic samples. Spectra measured at T=250 K.

agreement with Raikher model. When the dispersion in the directions of anisotropy axes of the particles is absent the contribution of inhomogeneous broadening to linewidth is negligible at low temperatures.

Such dependence can be explained on the basis of model of magnetic resonance in an ensemble of single-domain anisotropic particles [3]. The approach used based on the independent-grain model once proposed for the description of FMR in polycrystals [4]. The dependence of line width versus dimensionless parameter is:

$$\xi_0 = M_S V\omega/\gamma k_B T.$$

Here, M_s is saturation magnetization, V – volume of particles, ω - angular frequency, γ - gyromagnetic ratio, k_B - Boltzmann constant.

Asymptote (2) is described by:

$$\Delta H = (3\omega\varepsilon\xi_0)/(5\gamma),$$

here $\varepsilon = K\gamma/M_S\omega$, K – anisotropy constant.

As the temperature rises, the orientational fluctuations of the magnetic moment weaken the inhomogeneous broadening of the FMR line. This broadening arises from the dispersion in the directions of anisotropy axes of the particles.

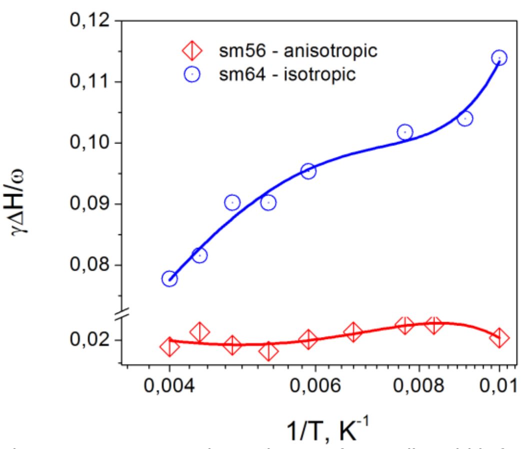

Fig. 2. Temperature dependence of FMR linewidth for isotropic and anisotropic samples.

It should be noted that FMR linewidth for anisotropic samples is nearly constant with temperature variation. This behavior is in a good agreement with Raikher model of magnetic resonance in an ensemble of single-domain anisotropic particles. When the dispersion in the directions of anisotropy axes of the particles is absent the contribution of inhomogeneous broadening to linewidth is negligible at low temperatures. Superparamagnetic broadening in this region is also insignificant. As a consequence the linewidth is practically temperature independent, at least in scale of relative variations. In summary, our FMR results show that isotropic samples consist of particles with randomly oriented easy magnetization axes whereas anisotropic samples – nearly unidirectional EMA.

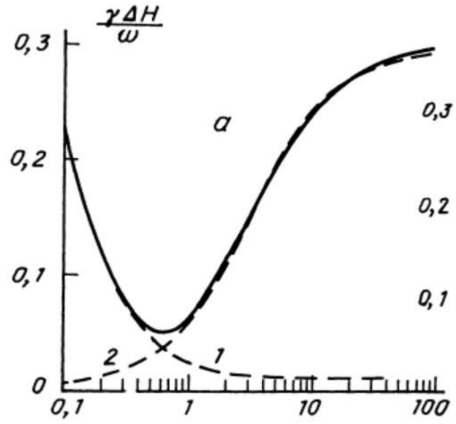

Fig. 3. Calculated linewidth ΔH vs parameter $\xi_0 \sim 1/T$ (Raikher theory). Dashed lines show the asymptotics: (1) – superparamagnetic broadening, (2) – inhomogeneous broadening. Reproduced from [2].

Conclusion

1) Significant difference in FMR linewidth for anisotropic and isotropic iron silicide films was revealed, FMR linewidth for isotropic films being temperature dependent.

2) The experimental results are well explained in the frame of Raikher model of magnetic resonance for dynamic susceptibility of ensemble of single-domain anisotropic particles.

3) FMR results show that isotropic samples consist of particles with randomly oriented easy magnetization axes whereas anisotropic samples – nearly unidirectional EMA.

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